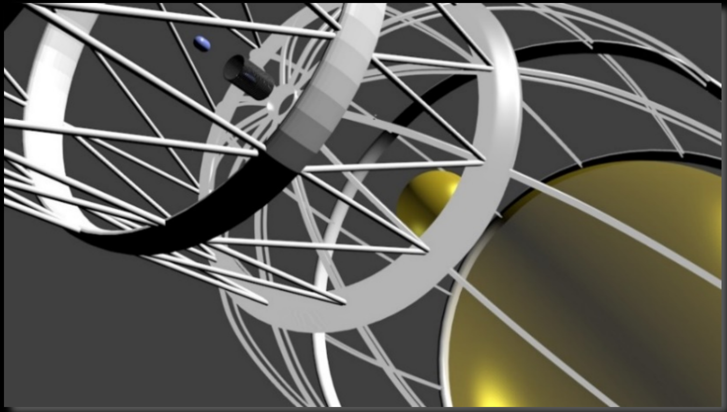
NASA Innovative Advanced Concepts

Gradient Field Imploding Liner Fusion Propulsion System

Phase I Study



Mike LaPointe, PhD/NASA Marshall Space Flight Center

Robert Adams, PhD/NASA Marshall Space Flight Center

Jason Cassibry, PhD/University of Alabama, Huntsville

Mark Zweiner, University of Alabama, Huntsville

Ross Cortez, University of Alabama, Huntsville

Jim Gilland, PhD/Ohio Aerospace Institute

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Human deep space exploration requires high energy propulsion systems

$$\frac{m_f}{m_0} = e^{-\Delta v / v_e}$$

- Solar system destinations require $\Delta v \approx 10^4 - 10^5$ m/s
- High exhaust velocity required for reasonable payloads

Multiple studies show the benefits of fusion energy for rapid trip times to Mars and the outer solar system…

- High exhaust velocity (specific impulse)
- High specific power (kW/kg) to reduce trip times

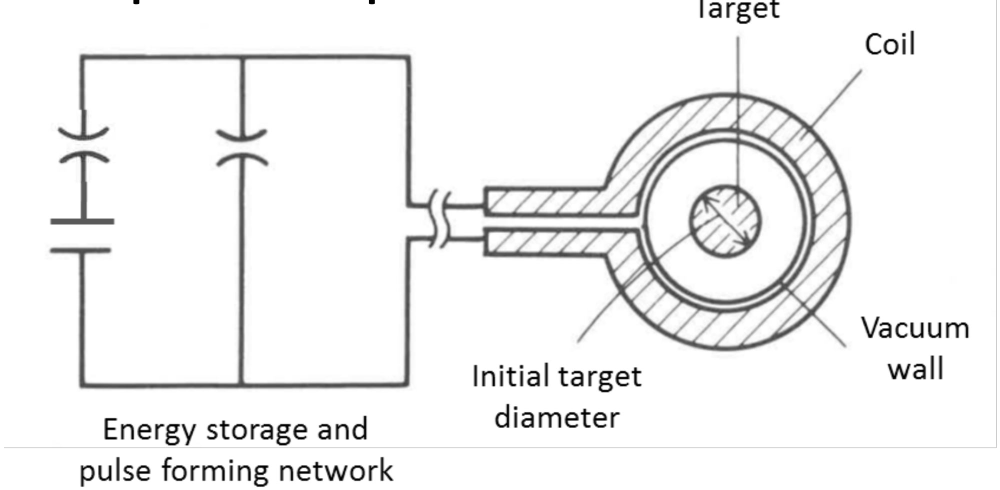
…once we get it to work

Rocket equation: (m_f/m_o) = fraction of initial mass delivered to destination; Δv = required mission velocity; v_e = propellant exhaust velocity

Take advantage of current ground-based research in Magnetoinertial Fusion (MIF)

Multiple approaches: Z-pinch, Θ-pinch, Liner-driven FRC, etc.

Θ-pinch concept



Adapted from Miyamoto, K. Plasma Physics for Nuclear Fusion, MIT Press, Cambridge, MA (1987)

- Pulsed current in an external coil generates strong axial magnetic field, induces azimuthal current in target liner
- Radial $j_\Theta B_z$ Lorentz force implodes the liner to compress the target fuel
- At maximum compression, pressure is balanced between the stagnating liner material, external magnetic field, trapped internal magnetic field, and fuel pressure

Energy storage, resistive coil, pulse repetition all present challenges

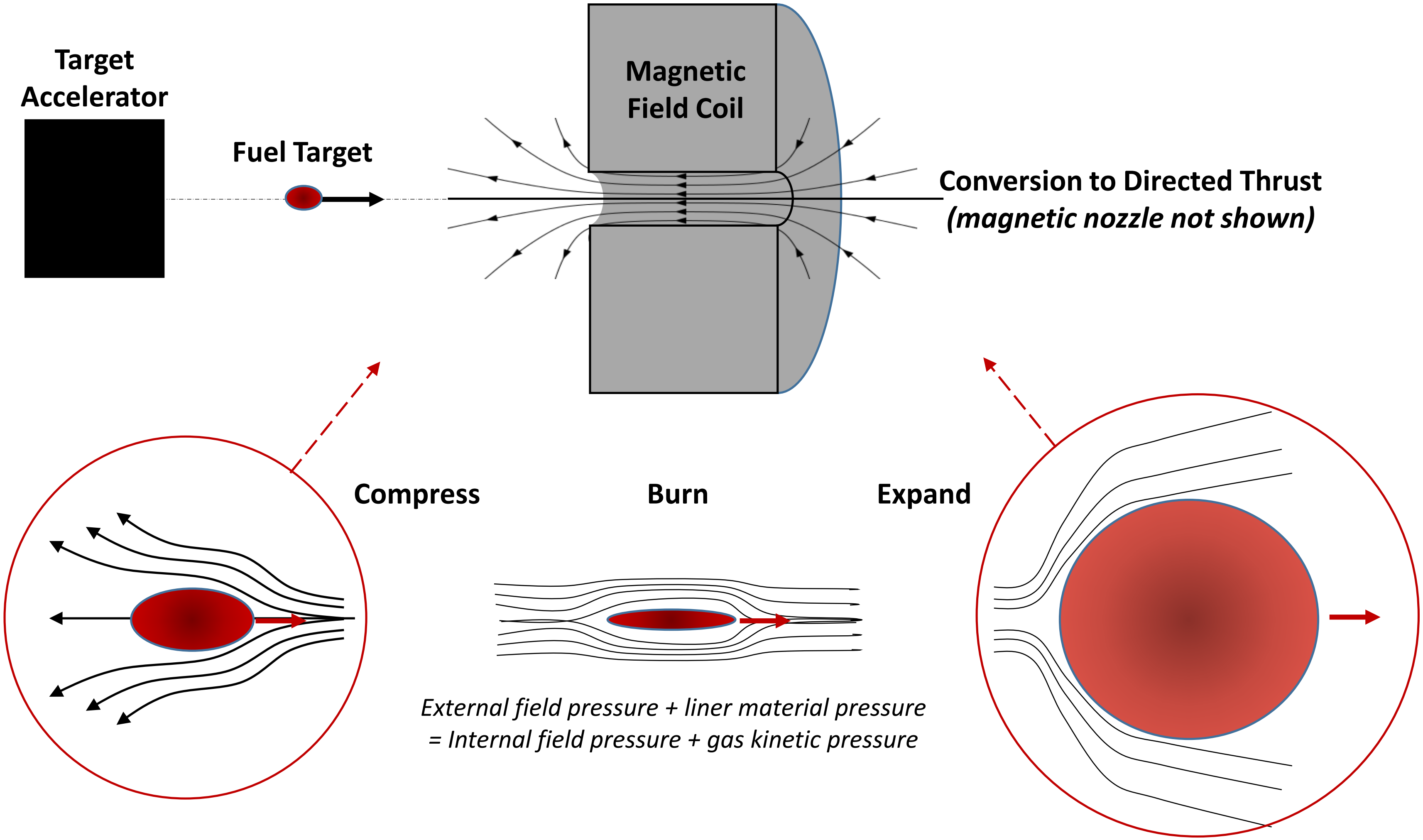
Reformulate the θ-Pinch Concept

- Replace the time changing magnetic field generated by the pulsed current coil with a target moving rapidly into a steady-state magnetic field gradient
  - Equivalent to a time changing magnetic field observed in the target frame of reference

$$\dot{I} \propto \dot{B}_z = v_z \frac{\partial B}{\partial z}$$

- The rapidly changing magnetic field observed in the target frame of reference induces a strong azimuthal current in the target liner
- The combination of axial magnetic field and azimuthal liner current generates a radial Lorentz force that rapidly compresses and heats the target, similar to a θ-pinch

Preliminary Concept



How Does This Help?

- Replaces pulsed drive coil with steady-state superconducting magnet, mitigating issues with repetitive, high current pulse generation
  - Reduces energy storage requirements, coil resistive losses
  - Reduces demands on switches, power components, etc.
- Fairly compact linear geometry for in-space applications
  - Strong gradient field produced by small bore magnet
  - Readily incorporates magnetic nozzle for directed plasma thrust
- Moves the challenge from pulsed coil to target accelerator
  - However, the target can be accelerated over a longer time period
- Opportunity for relatively low cost ground testing
  - Validate target acceleration, preheating, and compression physics
  - Adaptable once MIF conditions for fuel breakeven are demonstrated

Phase I Study Goals

- Model target injection and compression dynamics
- Evaluate fusion fuel target designs (geometry, density, liner)
- Evaluate high velocity target acceleration options (several km/s)
- Evaluate magnetic field requirements and solenoid coil designs
- Incorporate MIF concepts of target preheating and internally compressed magnetic fields to reduce particle thermal transport
- Estimate performance (yield, specific impulse, average thrust)

Pull it all together into an initial vehicle design and comparative mission analysis

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Phase I Study Approach

- Semi-analytic model (backup charts)
  - Based on McBride, R. and Slutz, S., "A semi-analytic model of magnetized liner inertial fusion," *Physics of Plasmas* **22**, 052708 (2015)
- Preliminary choices
  - Fuel: D+T -> α (3.5 MeV) + n (14.1 MEV)
    - easiest to ignite, but issues with neutrons
  - Accelerator: laser ablation to accelerate target
    - achieve high velocity, also useful for preheating target
- Performed several trades on target design, injection velocity, fuel density, magnetic field values, coil size, etc.
- Optimized design for maximum energy release, used to define vehicle performance for mission analysis

Summary of Results

Optimum Initial Parameters

Initial Fuel Density	Initial Target Radius	Aspect Ratio	Injection Velocity	Preheat Fuel Temp	Coil Axial B-Field	Initial Target B-Field	Axial B-field Gradient
0.07 kg/m^3	1.0 cm	6	10 km/s	400 eV	30 T	1.0 T	100 T/m

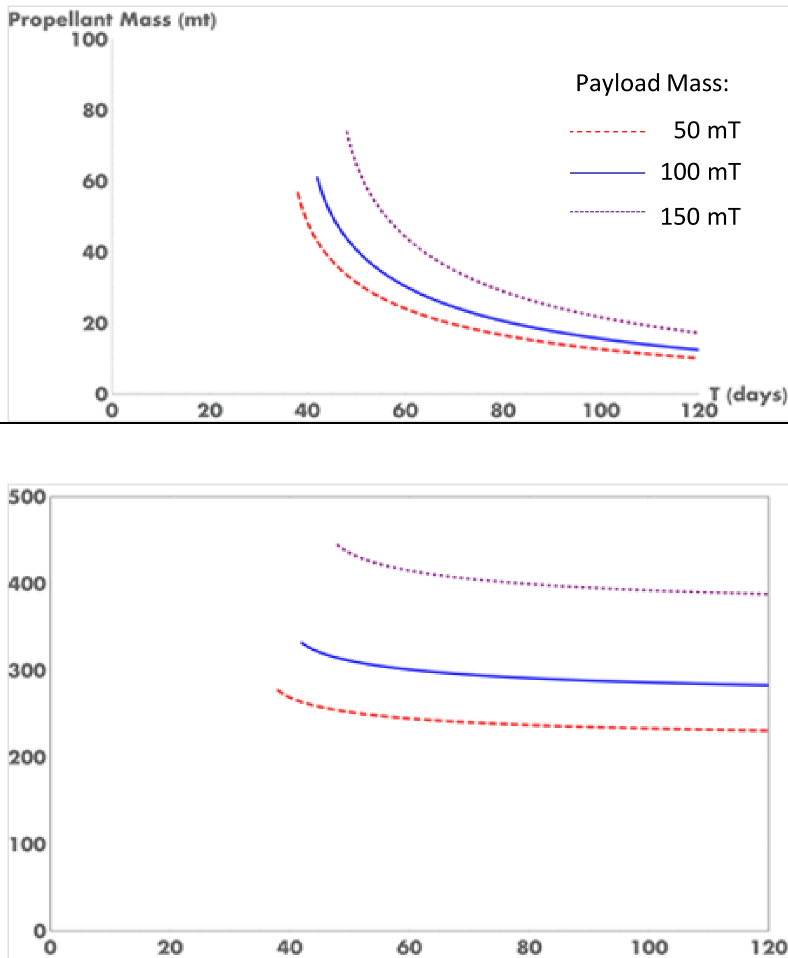
Corresponding Engine Performance

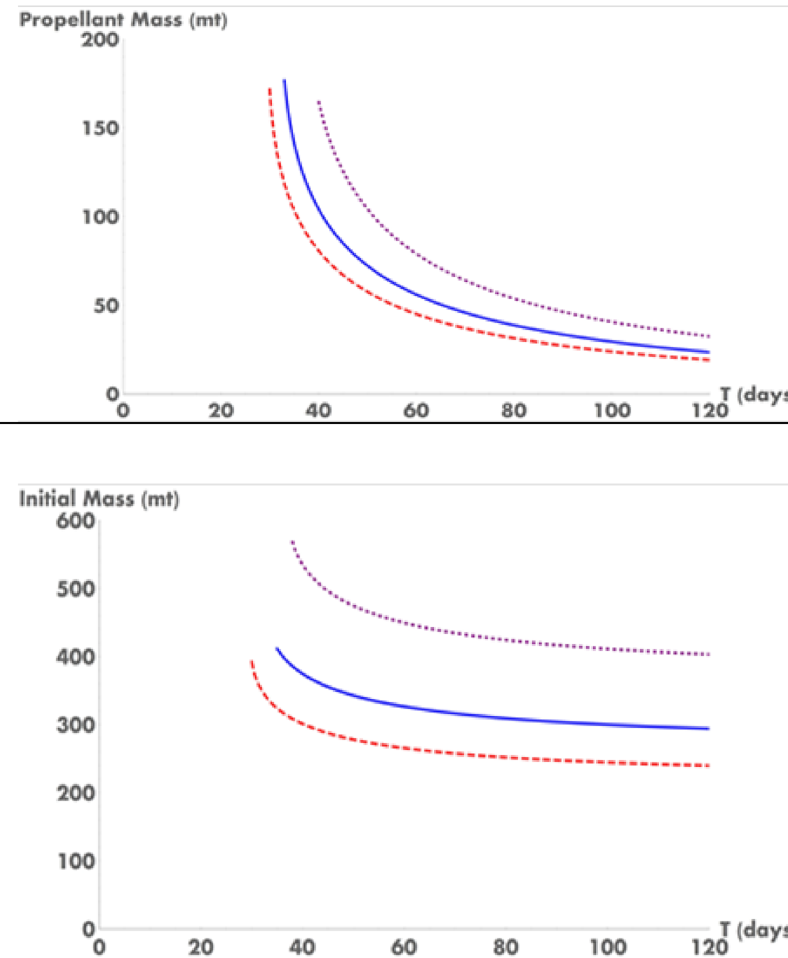
Specific Impulse (s)		Impulse (N-s)		Yield (J)		Gain (100% efficiency)	
Li Liner	Be Liner	Li Liner	Be Liner	Li Liner	Be Liner	Li Liner	Be Liner
32,200	**17,145**	**780**	**1445**	**1.65×10^8**	**1.53×10^8**	**982**	**323**

Assumes 70% magnetic nozzle conversion efficiency (plasma energy into directed kinetic energy)

Results are extremely optimistic, but demonstrate the concept is feasible and may provide performance values of interest for deep space exploration

Mission Analysis: Mars



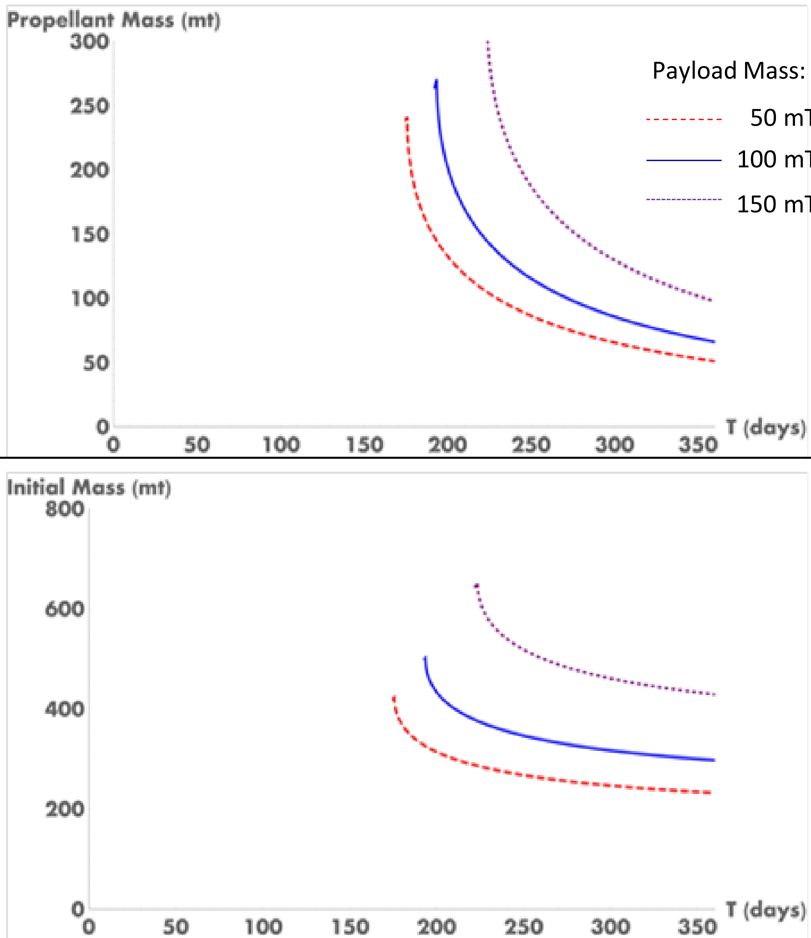


Mars propellant and total initial mass scaling for the Li liner gradient field fusion case.

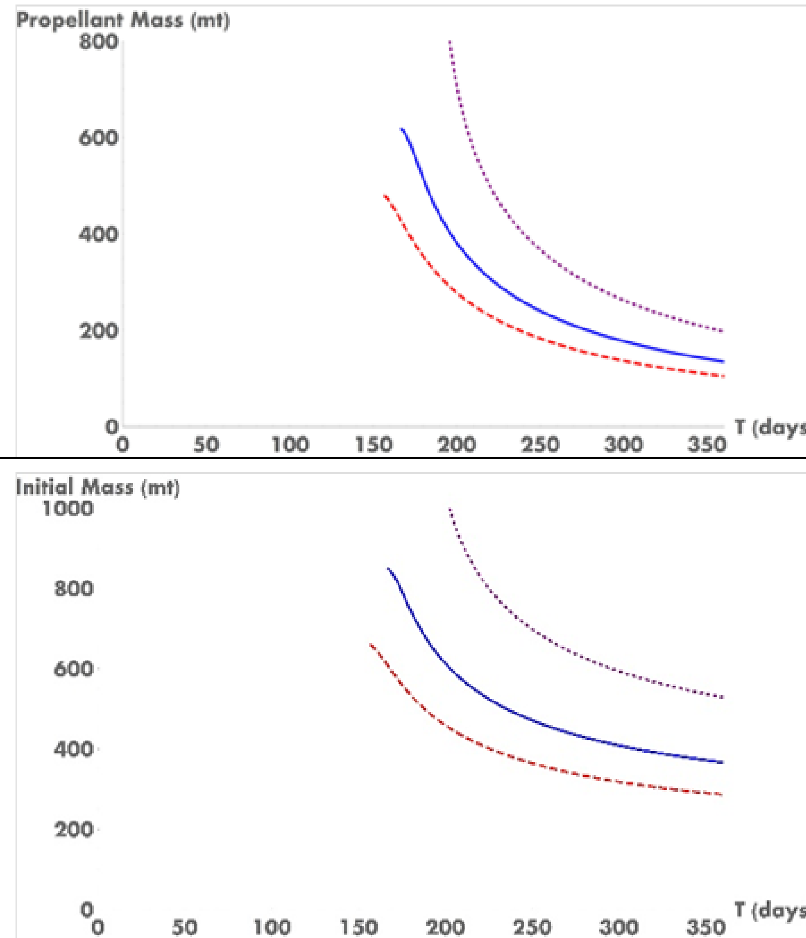
Mars propellant and total initial mass scaling for the Be liner gradient field fusion case.

Example: Initial vehicle mass of 320 mT with a 100 mT payload would take 45 days and use 50 mT of propellant for a 1-way trip to Mars with the Li lined target system, and approximately 75 days with the Be lined target system

Mission Analysis: Saturn



Saturn propellant and total initial mass scaling for the Li liner gradient field fusion case.

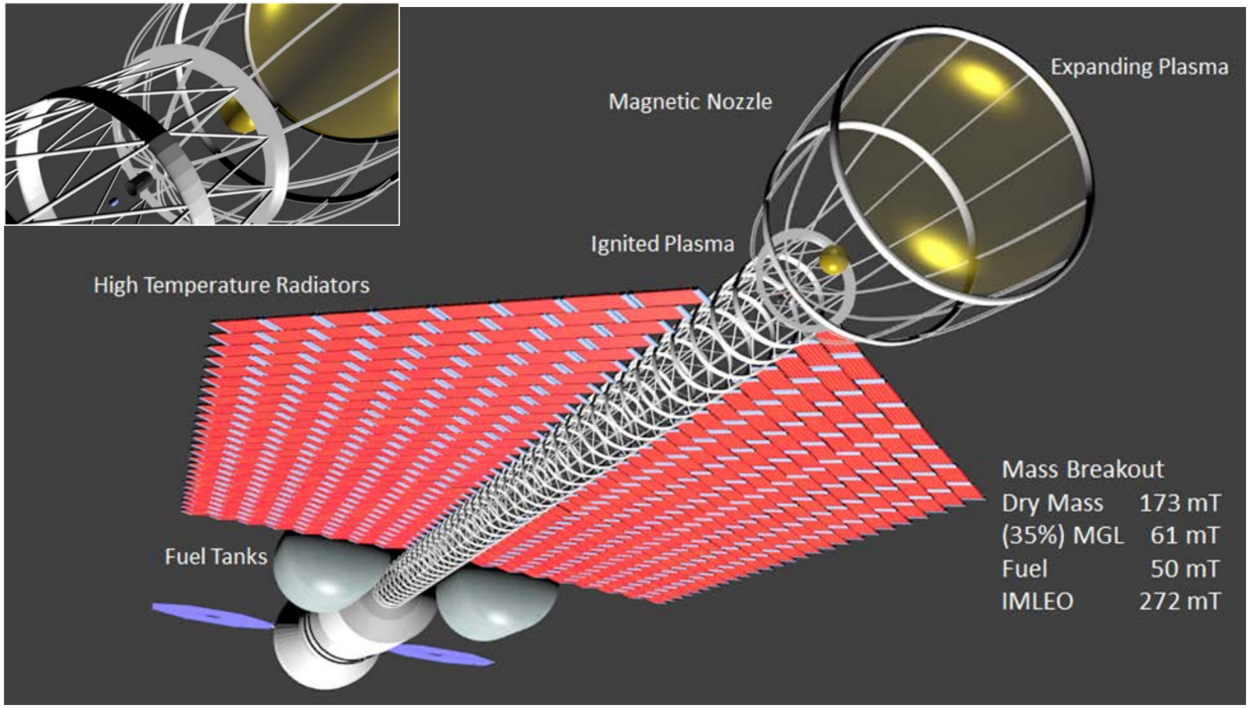


Saturn propellant and total initial mass scaling for the Be liner gradient field fusion case.

Example: Initial vehicle mass of 400 mT with 100 mT payload would take 200 days and use 190 mT of propellant for a 1-way trip to Saturn with the Li lined target system, and approximately 320 days with the Be lined target system

Preliminary Vehicle Concept

Rapid Mars trip with Orion module and deep space habitat



System	**Mass (mT)**
Prop Tanks	5.0
Thermal	13.6
Propulsion	75.4
Structural	17.3
Avionics	3.5
Mass Growth Allowance	58.4
Inert Mass	*173.2*
Payload	50.0
Dry Mass	*223.2*
Ullage	1.5
Inert Mass	*224.7*
Propellant	48.5
IMLEO	***271.6***

- **Mass parameters based on related prior work:**

  - Adams, R. B., R. A. Alexander, J. M. Chapman, S. S. Fincher, R. C. Hopkins, A. D. Philips, T. T. Polsgrove, et al. 2003. *Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets*, NASA-TP-2004-213089.
  - Miernik, J., G. Statham, L. Fabisinski, C.D. Maples, R. Adams, T. Polsgrove, S. Fincher, et al. "Z-Pinch Fusion-based Nuclear Propulsion," *Acta Astronautica,* 82 (2), pp. 173-182, 2013

Future Work

Advanced 3D multi-physics simulation (SPFMax)

- Smooth Particle Hydrodynamics with Maxwell equation solver developed by UAH for MIF and fission/fusion hybrid research
- Preliminary results show induced surface current generated due to $v_z(\partial B_z/\partial z)$ term

Ground-based experiment options (validation models)

- Experimentally demonstrate target compression physics
  - Available 2-stage light gas gun, hollow or filled projectiles, instrumented
  - Use water cooled coils to generate various magnetic field geometries
- Pulsed laser ablation studies of liner materials
  - Available kW-class pulsed laser, thrust stand

Currently evaluating approaches for a possible Phase II proposal

Acknowledgements

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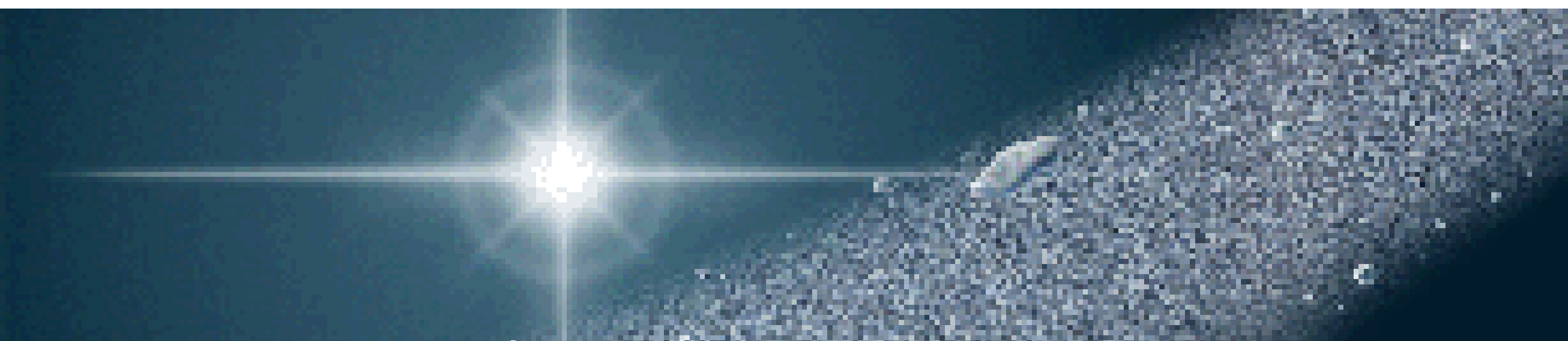
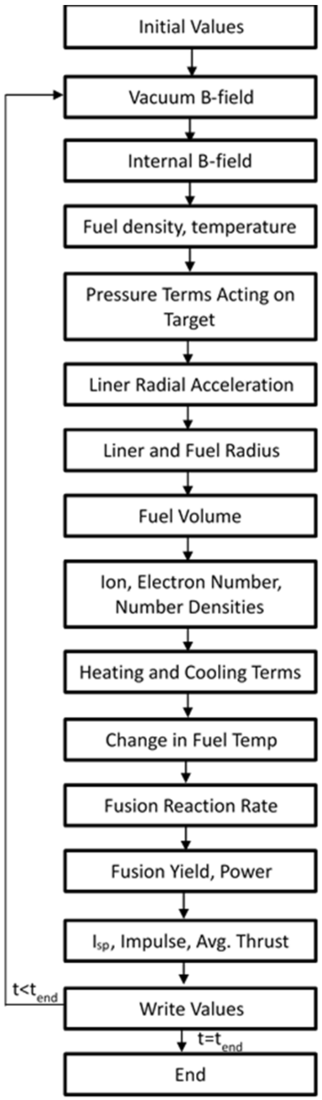
The Phase I final report will be available on the NIAC website

Study POC: Dr. Mike LaPointe
Space Technology Development Branch/ST23
NASA Marshall Space Flight Center, Huntsville, AL 35812
Email: michael.r.lapointe@nasa.gov; Phone: (256) 544-6756



BACKUP CHARTS

Phase I Study Approach



Semi-Analytic Model

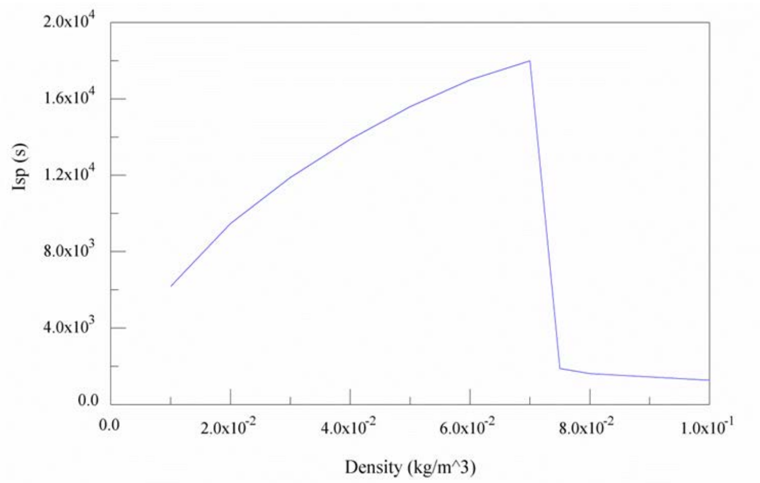
Based on MIF model of McBride and Slutz (2015)

- Adiabatic heating
- Optional fuel preheating (laser absorption)
- Fusion byproduct (α) energy deposition within target
- Radiative losses from high temperature plasma
- Radial ion and electron thermal conduction losses
- Mass and energy end losses from the compressed target
- Fusion cross sections and reaction rates
- Energy yield and gain, energy balance calculations
- Initial model modified for high velocity target injection
- Partially validated with adiabatic compression model

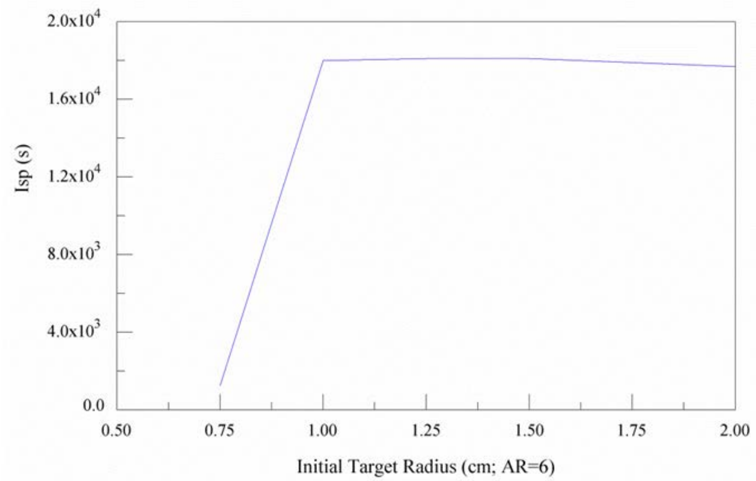
Numerous trade studies performed to evaluate optimum engine performance

McBride, R. and Slutz, S., "A semi-analytic model of magnetized liner inertial fusion," *Physics of Plasmas* **22**, 052708 (2015)

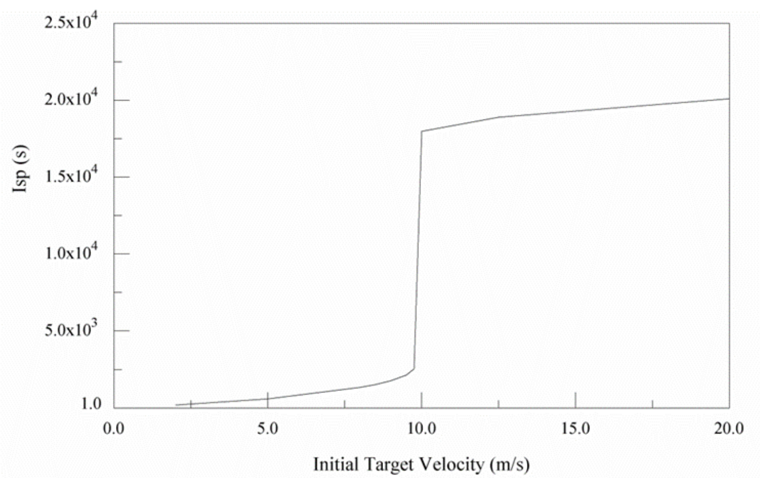
Sample Model Results



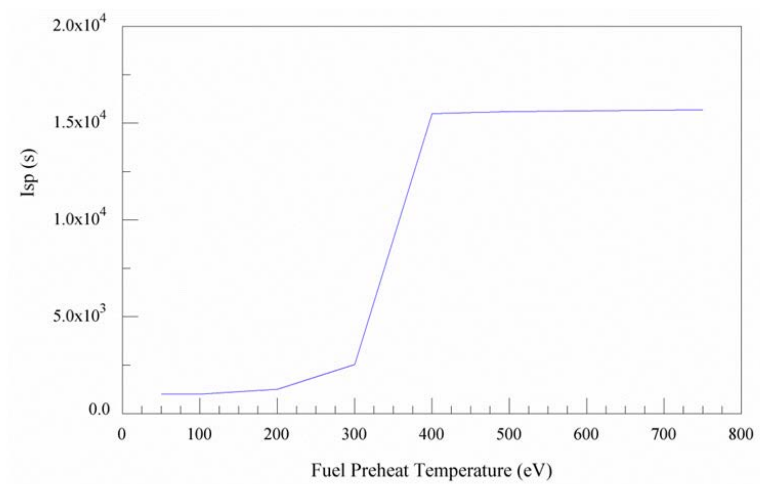
Isp as a function of initial fuel density



Isp as a function of initial target radius

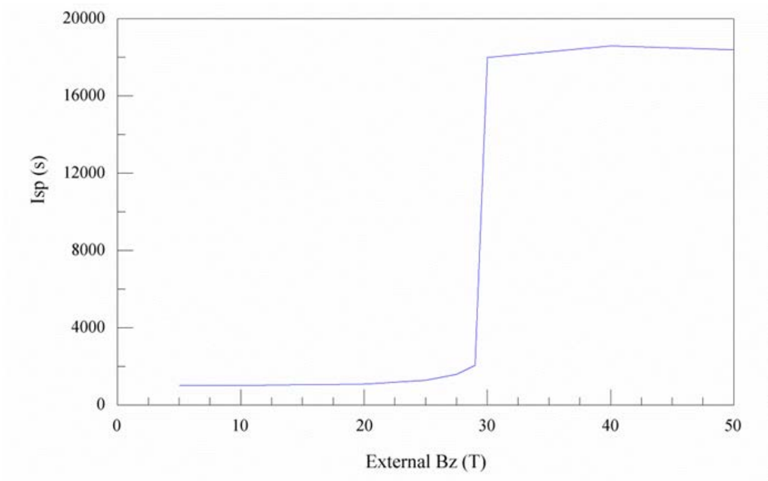


Isp as a function of initial target velocity

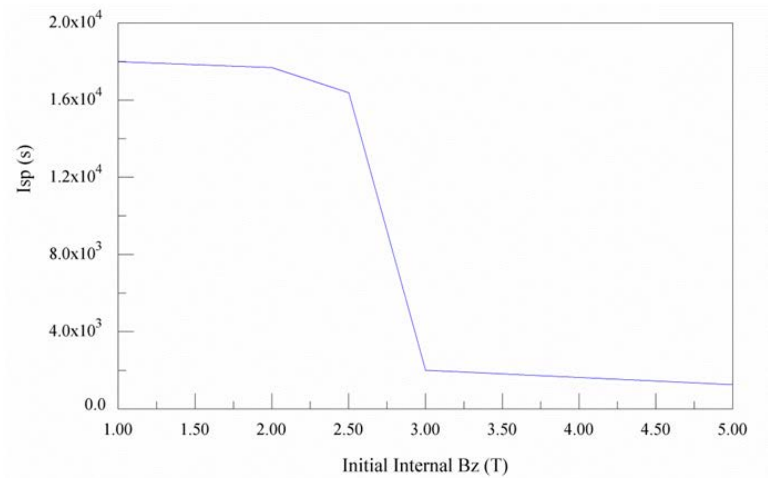


Isp as a function of fuel preheat temperature

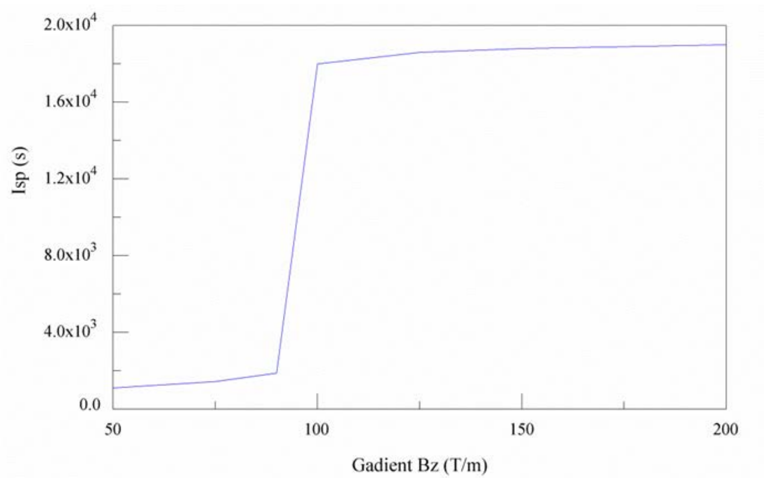
Results, continued



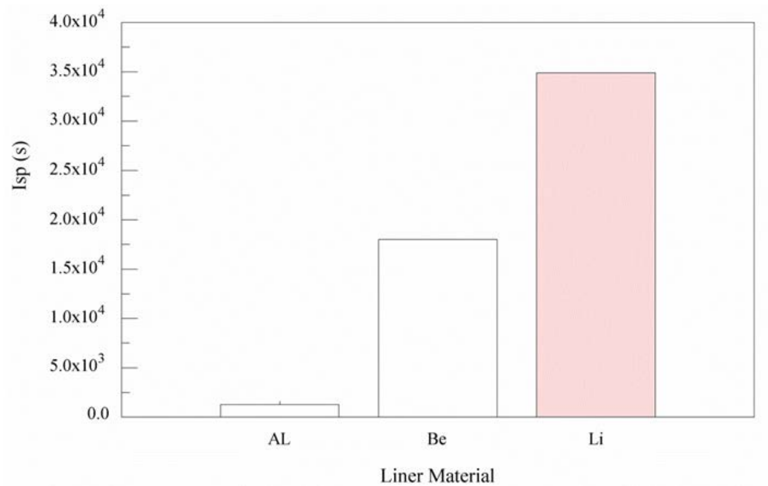
Isp as a function of external magnetic field



Isp as a function of internal target magnetic field



Isp as a function of magnetic field gradient



Isp as a function of liner material (Al, Be, Li)

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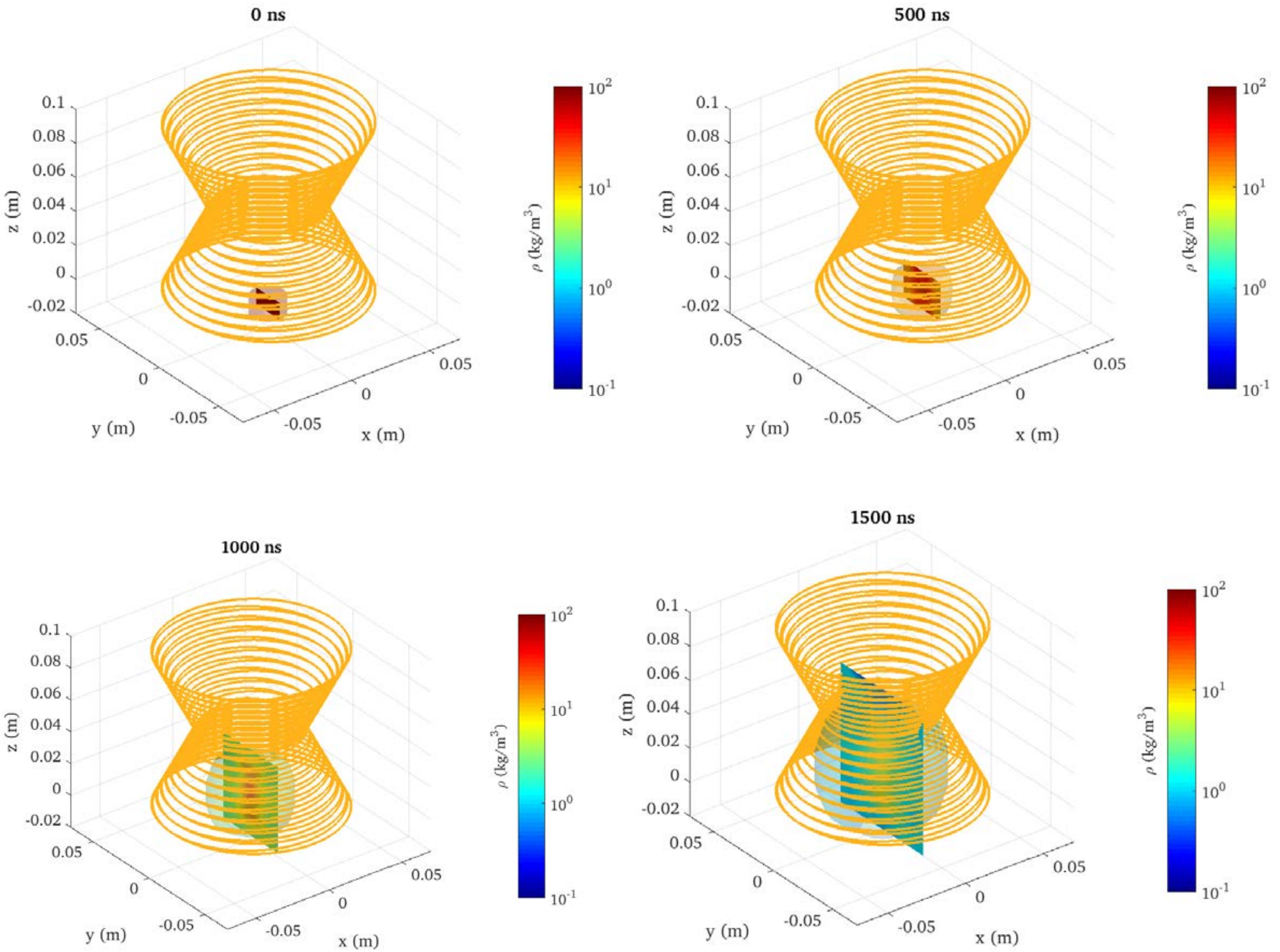
In Development: SPFMax Simulation

Smooth Particle Hydrodynamics with Maxwell equation solver

Code in development at the University of Alabama, Huntsville

- Tabular equations of state to model variable levels of ionization
- Thermal conduction, radiation emission and absorption
- Shock capturing
- Real viscosity
- Electromagnetic field propagation and forces in the plasma
- Self-consistent circuit model
- Nonlocal absorption of fusion ion product energy

SPFMax Simulation



Sequence of target propagation through the entrance of a magnetic field coil